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Scaling beyond 3D *XY* in the fluctuation conductivity of $YBa_2Cu_3O_{7-\delta}$

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Abstract

Systematic measurements of the in-plane fluctuation magnetoconductivity in a $YBa_2Cu_3O_{7-\delta}$ single crystal are presented. Fields up to 500 mT were applied either parallel or perpendicular to the Cu–O planes. The data reveal the occurrence of Gaussian-fluctuation regimes far from the transition. Closer to T_c, the results clearly show the occurrence of a genuine critical regime, where the exponent is consistent with predictions for the 3D *XY* universality class with model-*E* dynamics. Still closer to T_c, evidence is found for a fluctuation regime beyond 3D *XY*. This new scaling can be interpreted as revealing an ultimate first-order character of the superconducting transition in $YBa_2Cu_3O_{7-\delta}$.

Keywords: A. High-T_c superconductors; D. Electronic transport; D. Phase transitions

Thermodynamic fluctuations are observed in equilibrium and transport properties of high-T_c superconducting cuprates (HTSC) in large temperature intervals above and below the normal–superconductor transition [1]. Far above T_c, experiments can be interpreted in terms of Gaussian fluctuations of the order parameter [2–5]. Closer to T_c, careful studies of the specific heat [6,7], penetration depth [8], and electrical conductivity [9–11] are now consistently revealing effects of genuine critical fluctuations for a transition belonging to the three-dimensional (3D) *XY* universality class. It has been shown that the 3D-*XY* thermodynamics is robust even under weak to moderate magnetic fields [9,11–13]. However, the 3D *XY* model describes the critical behavior of a neutral superfluid with a two-component scalar order parameter, such as liquid ^{4}He [14]. As a superconductor is a *charged* superfluid, coupling of the order parameter to fluctuations of the electromagnetic field should be taken into account. Then, the superconducting transition may become weakly first-order, as suggested from a renormalization-group analysis by Halperin, Lubensky, and Ma [15]. It has been presumed that the reduced temperature interval where the transition reveals its first-order character, if existing [16], is very small and too close to T_c to be experimentally studied. Indeed, despite the considerable amount of detailed critical-behavior investigations in HTSC, authors do not refer to any evidence of a first-order pairing transition.

It is the purpose of this letter to report the existence of a power-law regime in the normal-phase fluctuation conductivity of $YBa_2Cu_3O_{7-\delta}$ (YBCO) which occur at reduced temperatures smaller than those where the 3D-*XY* scaling is identified. We will argue here that this new fluctuation regime may be indicating the ultimate first-order character of the superconducting transition in YBCO.

Our measurements were performed on a single-crystal sample, grown by a self-flux method in a YSZ crucible [17]. Oxygenation was performed for 6 days at 500°C. The crystal is uniformly micro-twined, and presents an oxygen content between 6.90 and 6.92. In-plane resistivity measurements were performed with a low-frequency, low-current AC technique which employs a lock-in amplifier as a null detector. Four in-line electrical contacts were silver painted on the sample. Magnetic fields in the range 0–500 mT could be applied either parallel or perpendicular to the

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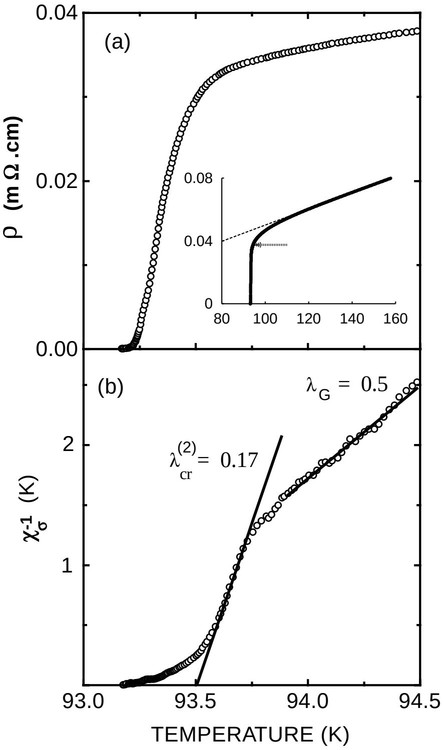

Fig. 1. Superconducting transition in YBCO plotted as (a) in-plane resistivity versus temperature and (b) inverse of the logarithmic derivative of the conductivity, χ_σ^{-1}, versus T. The quoted fluctuation conductivity exponents are determined from the slopes of the straight lines shown. The inset in panel (a) shows a representative measurement in an extended temperature range, with the regular contribution fitted to a straight line. The uppermost data point of the main plot is indicated by the arrow in the inset.

$Cu–O_2$ layers. The uncertainty in the field orientation is smaller than 3°. Temperatures were determined with a Pt sensor which has an accuracy of 1–2 mK and was corrected for magnetoresistance effects. Data points were recorded while increasing or decreasing the temperature in rates of 3 K/h or smaller, in order to assure that effects of thermal gradients were absent.

Our method of analysis is based on the numerical determination of the quantity [9]

$$\chi_\sigma = -\frac{\mathrm{d}}{\mathrm{d}T} \ln \Delta\sigma, \tag{1}$$

where the fluctuation conductivity $\Delta\sigma$ is obtained by subtracting from the measured conductivity the high-temperature regular term $\sigma_R = 1/(a + bT)$ extrapolated to the vicinity of T_c. Assuming that for low magnetic fields the field-dependent fluctuation conductivity diverges as a simple power-law [18],

$$\Delta\sigma(T,B) = A\varepsilon^{-\lambda}, \tag{2}$$

where $\varepsilon = (T - T_c(B))/T_c(B)$, in analogy with the Kouvel-Fisher method for analyzing critical phenomena, we obtain

$$\chi_\sigma^{-1} = \frac{1}{\lambda}(T - T_c). \tag{3}$$

Thus, the simple identification of a linear temperature behavior in plots of χ_σ^{-1} versus T allows the simultaneous determination of T_c and the critical exponent λ. Once determined the temperature range where scaling is observed, the critical amplitude A may be calculated from Eq. (2).

The main sources of uncertainties in our analysis come from numerical calculation of temperature derivatives, and from the extrapolation procedure to estimate σ_R. These errors, however, tend to be small at the transition, where a significant fraction of the total conductivity is due to fluctuations. Moreover, in order to minimize uncertainties, we performed the measurements, for each applied field, generally in four runs, two raising and two lowering the temperature. Power-law regimes were searched for in the data sets corresponding to each run. The resulting exponents were then averaged over the runs.

In Fig. 1 we show the resistive transition at zero field for our YBCO sample. In panel (a) we plot the measured resistivity as a function of T in a narrow temperature range around T_c. The inset shows the resistivity in a larger temperature interval, which allows the determination of the regular contribution, represented by the fitted straight line. In panel (b) of Fig. 1 the transition is shown as χ_σ^{-1} versus T. Two straight lines are fitted to the χ_σ^{-1} data. The one farthest from T_c is labeled by the exponent $\lambda_G = 0.5$, and corresponds to a regime dominated by 3D Gaussian fluctuations [19]. The critical amplitude corresponding to this regime allows us to calculate the coherence length perpendicular to the $Cu–O_2$ layers [20]. We obtain $\xi_c(0) = 0.11\,(\pm 0.01)\,\mathrm{nm}$, which falls in the range of the most accepted values for this quantity. The lower temperature limit of the Gaussian region gives an estimation of the Ginzburg number, for which we obtain Gi = 0.005. The straight line labeled by the exponent $\lambda_{cr}^{(2)} = 0.17$ identifies a critical scaling regime beyond 3D *XY* that will be discussed in the following paragraphs. The existence of such a regime was first noticed in Ref. [21]. A fluctuation-conductivity regime characterized by a small exponent was also reported in thin films of YBCO/Au composites [22]. Below the temperature region where this new regime is observed, we can see that the transition is rounded off. We interpret this as a finite-size effect due to the twin boundaries, since the studied sample is uniformly micro-twined, as we remarked before.

In Fig. 2 we show representative measurements of $\chi_\sigma^{-1}(T)$, for low applied fields, in the narrow temperature interval where *critical* fluctuations of the conductivity are observed. Both panels show that the genuine critical regime in YBCO has an internal structure. At least two power law regimes can be discerned. Fig. 2(a) is typical of results obtained in very low applied fields ($\mu_0 H \leq 4\,\mathrm{mT}$). It

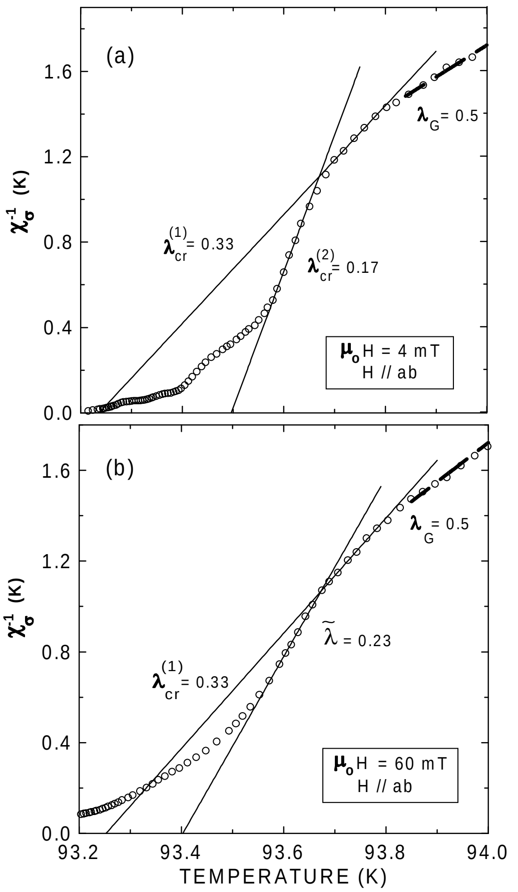

Fig. 2. Representative results of χ_σ^{-1} versus T in the critical fluctuation interval. The observed power law regimes are indicated by the respective exponents, which are discussed in the text.

shows that when the temperature is decreased towards T_c, and beyond the Gaussian λ_G-interval, we first observe a narrow region where the exponent is $\lambda_{cr}^{(1)} = 0.33\,(\pm 0.04)$, followed by a *new regime* characterized by the exponent $\lambda_{cr}^{(2)} = 0.17\,(\pm 0.02)$. This regime, which has a width of at most 0.1 K, is absent for fields above $\mu_0 H = 5\,\text{mT}$ ($H \parallel ab$). For higher applied fields, and up to $\mu_0 H \simeq 100\,\text{mT}$ when $H \parallel ab$ and 40 mT when $H \parallel c$, χ_σ^{-1} behaves as represented in Fig. 2(b). The regime with $\lambda_{cr}^{(1)} = 0.33$ is still observed, but the applied field enhances the rounding off of the transition closer to T_c, where an effective power-law regime with exponent $\tilde{\lambda} \simeq 0.23$ can be discerned. The amplitudes for the two relevant critical power laws are independent of the magnitude and orientation of the applied field. We obtain $A^{(1)} = 0.75\,(\pm 0.03)\,\text{m}\Omega.\text{cm}$ and $A^{(2)} = 0.34\,(\pm 0.01)\,\text{m}\Omega.\text{cm}$, respectively for the regimes associated with $\lambda_{cr}^{(1)}$ and $\lambda_{cr}^{(2)}$.

We turn now to the interpretation of our experimental observations. The critical exponent for fluctuation conductivity is given by [23]

$$\lambda = \nu(2 + z - d + \eta), \tag{4}$$

where ν is the coherence-length critical exponent, z is the dynamical exponent, d is the dimensionality and η is the exponent for the order-parameter correlation function. Renormalization-group calculations for the 3D *XY* model give $\nu \simeq 0.67$ and $\eta \simeq 0$ [24]. The dynamical universality class of the superconducting transition is a debatable subject. Recent experiments [9–11,25] indicate that the model-*E* theory of Hohenberg and Halperin [26], developed for the superfluid transition, should be appropriate. This model predicts that $z \simeq 3/2$, yielding a critical exponent $\lambda_{cr}^{(1)} = 0.33$ for fluctuation conductivity. This scaling behavior, which we call 3D-*XY-E*, was previously observed in polycrystalline [9] and single-crystal [10,11] YBCO, and also in $Bi_2Sr_2CaCu_2O_8$ [25]. In the present measurements, however, an additional regime is observed beyond the 3D-*XY-E* scaling, corresponding to the exponent $\lambda_{cr}^{(2)} = 0.17$, as commented above. We propose, as a possible interpretation, that this new scaling is associated with a weak first-order transition, based on the arguments presented below.

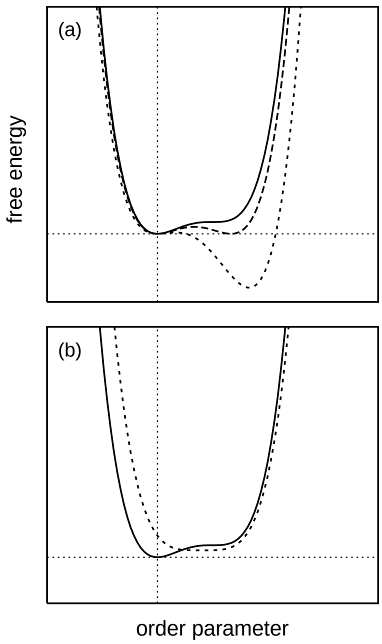

Fig. 3. (a) Schematic plot of a Ginzburg–Landau free energy with a cubic term in the order parameter yielding a first-order transition. (b) Free energy with the cubic term at the point where the second minimum starts to appear (full line), and without the cubic term at the critical temperature (dashed line). The latter is displaced from its central position to help visualizing the similarity between the two curves in the region of positive order parameter.

In a first-order transition, the Ginzburg–Landau free-energy F varies as a function of the order parameter as schematically represented in Fig. 3(a), where only non negative values of the order parameter $|\psi|$ are physically meaningful for a superconductor. The appearance of a minimum at non-zero $|\psi|$ is due to the presence of a third-order term in this parameter in the free energy. According to Halperin, Lubensky, and Ma [15], such a term originates from fluctuations of the electromagnetic vector potential. The transition occurs when the absolute minimum of F switches from its high-temperature position at $|\psi| = 0$ to the one with non-zero $|\psi|$. Above, but at close vicinity to T_c, the system can fluctuate between the two free-energy minima, due to the low height of the barrier separating them. This should affect the dynamics of the system near the transition, modifying the effective value of z. For instance, the critical exponent $\lambda_{cr}^{(2)} = 0.17$ may be obtained if $z \simeq 5/4$ in Eq. (4).

An alternative interpretation that does not involve changes in the dynamical exponent is based on the analysis of scaling for first-order phase transitions developed by Fischer and Berker [27]. They claim that a renormalization-group fixed point associated with n coexisting phases will present n distinct eigenvalues that scale with the dimension of the system, yielding a coherence-length critical exponent $\nu = 1/d$ when the first-order transition is driven by the temperature, as is the case here. Then, for $d = 3$, we would have ν reduced to approximately one-half of its value for the XY model. From Eq. (4) one sees that, keeping z and η unchanged, we would have the same reduction in λ, in excellent agreement with the ratio between $\lambda_{cr}^{(2)}$ and $\lambda_{cr}^{(1)}$.

Additional indication of the ultimate first-order character of the superconducting transition in YBCO is provided by the increase (~ 0.25 K) in the extrapolated critical temperature for the $\lambda_{cr}^{(2)}$-regime when compared to that obtained for the 3D-XY-E. In a second-order phase transition, T_c is reached when F flattens out around the equilibrium point at $|\psi| = 0$. If the transition is weakly first-order, F would appear as effectively flat at a higher temperature, when the minimum at non-zero $|\psi|$ starts to appear. In Fig. 3(b) we plot the free-energy corresponding to this situation in comparison with the one for a purely second order transition at the critical point, showing their close similarity, mainly in the physically-significant region $|\psi| \geq 0$. Thus, if a power-law behavior is present, the cubic term in the free energy tends to effectively increase the extrapolated value of T_c with respect to the one that would be obtained if the transition remained strictly second-order. This effect could account for the somewhat paradoxical results of Fig. 2, where critical fluctuations seem to shift the critical temperature upwards.

We would like to stress that the temperature range in which the first-order nature of the transition becomes noticeable in our data, although smaller than the critical region itself, has the same order of magnitude. According to Ref. [15], one should expect it to be smaller by a factor κ^{ϕ}, where κ is the Ginzburg–Landau parameter (the ratio between the penetration depth and the correlation length), and ϕ is a crossover exponent. The latter should be roughly equal to the correlation-length exponent ν in three dimensions if the mechanism proposed by Halperin, Lubensky, and Ma [15] were responsible for the first-order transition. This does not hold in our case, since κ is very large, predicting a much narrower width of the first-order transition than the observed one. Thus, either the crossover exponent ϕ is strongly changed (e.g. by dynamical effects) or the mechanism driving the first-order transition in high-T_c superconductors is a new one, not necessarily related to fluctuations of the electromagnetic field. A plausible candidate for this mechanism in the HTSC is discussed in the work of Blagoeva et al. [28]. These authors present extensive renormalization-group calculations on generalized Ginzburg–Landau models to investigate the transition in superconductors with unconventional order-parameter symmetries. According to them, the combined action of cubic and orthorhombic anisotropies creates a favorable scenario for a first-order superconducting transition induced by thermal fluctuations.

In summary, our study of fluctuation conductivity in YBCO under applied magnetic field reveals that: (i) Far above T_c the results are well described by the Gaussian approximation. (ii) Closer to T_c, the transition is approached within the 3D-XY scaling with model-E dynamics. The observed 3D-XY-E scaling is essentially a zero-field one, since for $\mu_0 H \geq 0.1$ T ($H \parallel ab$) or $\mu_0 H \geq 0.04$ T ($H \parallel c$) criticality is rounded off. (iii) Still closer to T_c and in very low fields, a scaling regime beyond 3D-XY-E was observed. The value of the critical exponent for this regime, as well as the fact that the extrapolated critical temperature is displaced to a higher value, led us to suggest that this is indicative of the ultimate first-order character of the superconducting transition in YBCO. It would be interesting to have these results corroborated by measurements of quantities not affected by dynamical aspects, such as the specific heat or the magnetic susceptibility.

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